

09/834432

Docket No.: GK-ZEI-3117/500343.20118

METHOD AND ARRANGEMENT FOR THE SELF-CALIBRATION OF A DIODE
PUMPED SOLID STATE LASER, PARTICULARLY A TUNABLE,

5 DIODE PUMPED SOLID STATE LASER

BACKGROUND OF THE INVENTION

a) Field of the Invention

10 The invention is directed to a method and arrangement for the self-calibration of a diode pumped solid state laser (DPSSL), particularly a tunable, diode pumped solid state laser, in which the cavity length is changed for tuning the frequency of the radiation of the laser.

15 b) Description of the Related Art

It is known from DE 42 42 862 in a solid state laser pumped by laser diodes that the laser-active medium is contacted by a piezoelectric foil which is contacted in turn by an out-coupling mirror. The length of the air gap between the lasing medium and the out-coupling mirror is adapted. Mode selection is achieved by
20 suitable selection of the reflectivity of the mirror. This air gap has a length such that an optional selection of individual laser transitions, Q-switching or tuning of the laser frequency is made possible when voltage is applied to the piezoelectric foil.

DE 40 41 131 A1 and DE 40 42 440 A1 describe a solid state laser with longitudinal single-mode operation whose laser crystal is optically pumped by
25 laser diodes. A piezo-ceramic provided with a high-voltage generator (HV generator) for matching and modulating the wavelength and the fundamental and frequency-doubled radiation is associated with the doubling crystal. The tuning of the fundamental wavelength and second harmonic of the solid state laser is carried out by means of a variable change in the cavity length via the total amplification bandwidth.
30 Different cavity lengths and a change in the longitudinal modes are achieved by means of a variable positioning of the out-coupling mirror.

09/834432

The laser and the doubling nonlinear crystal are spatially separated from one another and a piezo-ceramic which is controllable by an HV generator is associated with the nonlinear crystal.

5 It is known from DE 36 43 648 C2 to provide an etalon in the form of an optical plate of small thickness for suppression of the amplitude noise in the resonator cavity in laser-diode pumped solid state lasers with intra-cavity frequency doubling, wherein the resonator cavity is preferably arranged at the location of a beam waist in order to minimize optical losses as well

10 OBJECT AND SUMMARY OF THE INVENTION

It is the primary object of the invention to provide a method and an arrangement for calibration in a tunable, diode pumped solid state laser which make it possible to compensate long-duration drift through self-calibration before every scan or as needed and thus, with an expandable tuning range of the laser, to always
15 optimize the output power of the laser.

According to the invention, this object is met in a method for the self-calibration of a tunable, diode pumped solid state laser in which the frequency of the laser radiation of the fundamental frequency and/or the wavelength of the laser radiation of the fundamental frequency and/or doubled frequency is changed
20 comprising the step of changing the optical cavity length by a piezo-actuator or Brewster window over the total amplification bandwidth of the laser-active material and, further including the steps of recording and storing the performance curves during the tuning of an etalon or corresponding optical elements arranged on the cavity, generating or deriving a tuning function for the respective optical element or
25 optical elements from these curves by a microcontroller or computer and adjusting an optimum working point for the optical element or optical elements for maximum suppression of side modes by a digital or analog regulator with the help of a learning curve or learning characteristic.

An arrangement for the self-calibration of the diode-pumped solid state
30 laser which comprises a laser diode as pump light source followed by in-coupling

optics, a laser crystal followed by out-coupling optics or a nonlinear, frequency-doubling crystal, wherein the outer surfaces of the laser crystal and doubling crystal or out-coupling mirror have a reflective coating for the laser fundamental frequency and/or for the frequency-doubled radiation and enclose the cavity between them, and
5 further comprises an actuator for varying the cavity length for purposes of tuning the laser is characterized primarily in that an etalon is provided inside the cavity for changing the tuning range and for determining the output power, wherein the etalon is rotatable or swivelable about an axis of rotation which extends at right angles to the optical axis of the laser or is inclined relative to the latter at a small angle.

10 In order to achieve a multiplication of the frequency of the radiation of the laser, a plurality of suitable nonlinear crystals can be arranged following the laser crystal.

Further details and developments of the invention are disclosed in the additional, dependent claims.

15 Accordingly, in order to record a learning curve, it is advantageous to tune the etalon or an optical element with increasing amplitude and to correct the deviation from the optimal position at the edge of the tuning range of another optical element. Accordingly, it can also be advantageous when the movement or adjustment of the etalon is adapted to the change in the length of the cavity.

20 Further, it is advantageous when optimizing an optical element that the latter is itself modulated or another optical element is modulated.

Accordingly, by means of modulating the optical element, a tuning characteristic of the latter or of another optical element is determined and stored.

25 Further, it is advantageous when the frequency-selective elements of the laser are adjusted between two mode jumps by means of a microcontroller or computer according to the recorded laser characteristic in such a way that side modes are suppressed to a maximum degree.

It is further advantageous when the learning characteristic is adjusted in that the cavity length determining the frequency is tuned as the "finest" frequency-selective element of the laser with increasing amplitude and the mode jumps occurring
30

at the edge of the tuning range are detected (registered) by a suitable measuring instrument or via the output of the laser. The movement of the next coarsest frequency-selective element at the edge of the tuning range is then changed (adapted) until a frequency jump (in the characteristic) no longer occurs. The entire position
5 (movement) of the coarse element is then stored.

Further, according to the method, the power curve or performance curve of the laser is advantageously recorded with a change of the rotational angle δ of the etalon and constant cavity length and with a change in the cavity length and a stationary etalon.

10 In the arrangement for the self-calibration of the DPSSL, it is advantageous when the etalon is constructed as a transparent disk which is rotatable or swivelable about the axis of rotation and its angle is adjustable by an angular drive.

A stepper motor, known per se, at least one of whose coils is controllable by means of a controlling circuit, can be provided as a drive device.
15 However, a piezo-actuator in operative connection with the etalon directly or with the intermediary of additional elements can also be provided as drive device, wherein it is advantageous that the piezo-actuator comprises a bending element as driving element.

Further, it may be advantageous that only one coil of the stepper motor is controlled. It can also be advantageous when both coils of the stepper motor are
20 controlled, wherein the field vector is modulated to prevent hystereses. The motor can also advantageously be operated in microstep operation.

It has proven advantageous when the rotational axis or shaft of the etalon is arranged so as to be inclined at an angle δ of less than 10° in relation to the vertical line to the optical axis of the laser.

25 The cooling of the moving elements is realized advantageously and by simple techniques by means of an element with good heat conductivity, preferably made of copper or another suitable material. In this respect, it is advantageous when an element is provided for this purpose.

In order to prevent formation of parasitic etalons, the crystals and other optical elements arranged in the cavity are advantageously constructed in a wedge-shaped manner.

Further, a standing wave cavity can be provided in such a way that a secure single-frequency operation is achieved by means of suitable matching of the selectivity of the etalon with the suppression of side modes by spatial hole burning achieved by the arrangement and selection of thickness of the laser crystal.

In another advantageous construction, a piezo-actuator with a stationary etalon is provided for tuning the laser, wherein the free spectral range of the etalon is greater than the amplification bandwidth of the laser crystal and the fineness is selected in such a way that a secure single-frequency operation is ensured in the maximum tuning range. It may also be advantageous that the etalon takes part in the movement to achieve a larger tuning range.

The invention will be described more fully with reference to the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

Fig. 1 is a schematic top view showing the construction of the solid state laser with motor-driven etalon;

Fig. 2 shows a side view of the solid state laser;

Fig. 3 shows a solid state laser with piezo-actuator for tilting the etalon;

Fig. 4 shows a solid state laser with piezo-actuator and copper ring;

Fig. 5 shows a solid state laser with wedge-shaped crystals and optical elements;

Fig. 6 shows a performance curve of a DPSSL; and

Fig. 7 shows a frequency curve.

In the individual Figures, identical reference numbers are used for parts and subassemblies having identical functions.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The DPSSL shown schematically in several views in Figs. 1 and 2 comprises a laser crystal 1 and, as pumped light source, a pump diode 2 or a
5 corresponding arrangement of a plurality of such diodes. The pump radiation emitted by the pump diode 2 is focused on the laser crystal 1 by imaging optics 3 arranged downstream in order to excite the laser crystal 1 for lasing. The laser crystal 1 is followed in the direction of the optical axis 4 of the laser arrangement by, in sequence, an angularly adjustable etalon 5, for example, a transparent, disk-shaped solid state
10 etalon, and a nonlinear crystal 6, for example, KTP, which doubles the frequency of the radiation of the laser crystal 1. This etalon 5 is used for changing, above all, expanding, the tuning range and also for adjusting and determining the output power of the laser crystal 1. The frequency-doubled radiation 8 is coupled out via an out-coupling element 7 which in the present example is a beam splitter element. A beam
15 component 9 (Fig. 2) of the radiation 8 is cut out in a manner known per se by the out-coupling element 7 for measurement purposes and is fed to a measurement element 10 for generating measurement signals.

The etalon 5 is advantageously fixedly arranged on a rotational shaft
11 which is in an operative connection with a drive 12 and can be rotated or swiveled
20 by the latter. For example, a stepper motor, known per se, is provided in Fig. 1 as a drive 12. The rotational shaft 11 extends vertical to the optical axis 4 of the laser arrangement or is inclined relative to the optical axis 4 at a small angle ($\delta < 10^\circ$). This prevents the occurrence of cavities coupled in the middle position during rotation of the etalon 5, which could lead to undefined frequency jumps. The drive 12, for
25 example, the coils of a stepper motor, communicates with a control device 13 and is controlled by the latter in a corresponding manner. The tuning range of the laser can be expanded by this rotation of the etalon 5 and its output power can be optimized. The measurement element 10, for example, is provided for measuring this output power.

It is advantageous when the etalon 5 is fastened directly to the shaft (rotational axis 11) of the stepper motor, which provides for a simple construction with additional gear units or intermediate gears and prevents additional hystereses in the course of movements of the etalon 5 as well as other mechanical control problems.

5 When a stepper motor is used as the drive 12, either only one coil or both coils can be controlled by means of the control device 13. Controlling only one coil simplifies the control of the stepper motor on one hand and, on the other hand, it is possible to remain within the gearing (pitch) of the stepper motor once this has been set; this means that the etalon 5 is always in a virtually correct position and the control
10 need not hunt blindly for a starting position without a regulating signal. In order to achieve the necessary angular resolution in the adjustment of the etalon 5, microstep operation is required in controlling the stepper motor by means of the control device 13, i.e., the rotation of the etalon 5 must be carried out in small steps or the coils must be controlled with an analog signal, which makes it possible to change the etalon
15 angle in a continuous manner.

When both coils of the stepper motor are controlled by corresponding modulation of the field vector, the position of the etalon 5 does not change. In this way, "soft" hystereses can be prevented.

In the other case, the position of the etalon 5 is modulated. This
20 prevents "soft" and "hard" hystereses. The frequency of the laser is not changed in this way.

"Soft" hystereses are, for example, hystereses caused by residual magnetization when an element does not exactly follow a control voltage, but "lags" behind it. "Hard" hystereses are those occurring, for example, by means of
25 mechanical play between cooperating parts or elements.

Individual elements of the laser arrangement have highly-reflective (HR) or anti-reflective (AR) coatings. Accordingly, the elements of the imaging optics 3 have AR layers for the pump radiation. The surface 1.1 of the laser crystal 1, on the other hand, is coated in such a way that it is anti-reflective (AR) for the pump
30 radiation and highly-reflective (HR) for the radiation of the laser crystal 1

(fundamental wave). The surface 1.2 of the laser crystal 1 is AR for the fundamental wave of the laser crystal 1 so that it can be supplied to the frequency-doubling crystal 6 without hindrance, but is HR for the pump radiation and also for the frequency-doubled radiation 8. The surfaces 5.1 and 5.2 of the etalon 5 has a reflection factor between 10% and 40% for the radiation of the laser crystal 1 or are not coated. The surface 6.1 of the doubling crystal 6 is HR for the frequency-doubled radiation with crystals which are not wedge-shaped and AR for the radiation of the laser crystal 1. The surface 6.2 of the crystal 6 is HR for the fundamental wave and AR for the frequency-doubled radiation of the doubling crystal 6. The coated surfaces 1.1 and 6.2 enclose the actual laser cavity.

The doubling crystal 6 can also be replaced by an out-coupling element when frequency doubling is not to be carried out. In this case, the cavity is determined by the surface 1.1 of the laser crystal 1 and by a surface of the out-coupling element (not shown) which is now used instead of the doubling crystal 6.

The construction of the DPSSL shown in Fig. 3 comprises, between the laser crystal 1 and the doubling crystal 6, an etalon 14 or another frequency-selective element which is fastened to an annular component 15, e.g., a metal ring. The etalon 14 is swivelable about an axis 16 which is arranged at right angles to the optical axis 4 of the laser. A piezo-actuator 17 which is connected, via the connections 19, with a control device 18 and is controlled by the latter is provided for generating the swiveling or tilting movement of the etalon 14. The piezo-actuator 17 is formed as a bending element in the example, However, a piezo element of a different construction, for example, one which changes in length, can also be provided. It is only important that the swiveling of the etalon 14 can be realized in small angular increments.

The surface 1.1 of the laser crystal 1 is HR for the laser light and AR for the wavelength λ_p of the light of the pump diode 2. The surface 1.2 is AR for the wavelength λ_L of the light of the laser crystal 1. The surface 6.1 of the doubling crystal 6 is AR for light of wavelength λ_L , while the surface 6.2 is HR for wavelength λ_L and AR for wavelength λ_D of the frequency-doubled light.

Also in this embodiment form, the cavity is determined by surfaces 1.1 and 6.2. In order to change or adjust the length of this cavity, another piezo-actuator 20 is provided, for example, wherein the frequency-doubling crystal 6 or an out-coupling mirror (not shown) contacts this additional piezo-actuator 20 as is shown in a simplified manner in Fig. 3. With appropriate control of the piezo-actuator 20, the cavity length can be deliberately changed and adjusted. In this way, the laser can also be correspondingly tuned. The length of the cavity is on the order of several mm, but can also be less than 5 mm.

The construction of the laser, according to the invention, shown in Fig. 4 comprises, in addition to the component parts mentioned in connection with Fig. 1, a preferably thin ring 21 which contacts the surface 6.1 of the doubling crystal 6 and which is made of a material with good heat conductivity, e.g., copper, which serves to effectively dissipate heat from the doubling crystal 6. Instead of the doubling crystal 6, an out-coupling mirror can also be arranged if no frequency doubling is provided. In this arrangement, the doubling crystal 6 is likewise connected with one end of the piezo-actuator 20, its other end contacting a mounting 22 or receptacle, for instance. The position of the doubling crystal 6 can also be varied and adjusted in the direction of the optical axis 4 by the piezo-actuator 20.

Fig. 5 shows a construction in which a wedge-shaped laser crystal 23 is provided. Further, the doubling crystal 24 is also designed in a wedge-shaped manner. Wedge-shaped crystals serve to prevent parasitic etalons which lead to a reduction in the power of the laser.

In the method for self-calibration of a tunable, diode pumped, solid state laser in which the frequency or the wavelength of the laser radiation of the fundamental and/or doubled frequency is changed by means of changing the optical cavity length by means of a piezo-actuator 17; 20 or a Brewster window via the total amplification bandwidth of the laser-active material of the laser crystal 1, the performance curves during the tuning of an etalon 5; 14 or corresponding optical elements which are arranged in the resonator are recorded and stored. A tuning function for the respective optical element or optical elements is generated or derived

from these performance curves by means of a microcontroller or computer 25, and an optimum working point for the optical element or optical elements for maximum suppression of side modes is adjusted by means of a digital or analog regulator with the help of a learning curve (learning characteristic).

5 The frequency is tuned by changing the cavity length, e.g., by means of the piezo-actuator 20 (Fig. 4), in the single-frequency laser under consideration.

 Accordingly, the piezo-actuator 20 can also be modulated initially with a small amplitude and then with increasing amplitude and the power (or efficiency) can be measured. The etalon 5 (Fig. 4) is adjusted in such a way that the power is at a
10 maximum (offset position) and receives a feed forward signal whose control curve is stored after every pass and whose shape is varied.

 The etalon 5; 14 can be rotated, e.g., by means of the drive 12 or the piezo-actuator 17, about the rotational shaft 11 extending at right angles or virtually at right angles to the optical axis 4 in order to expand the tuning range of the laser and
15 optimize its output power. This output power can be measured by the measuring element or a photodiode. In this connection, the principal problem which arises is that the movement of the etalon 5;14 must be adapted exactly to the change in length of the cavity, which is difficult since a root function is used for the linearization of the frequency path or response of the etalon, and hystereses, nonlinearities and long-
20 duration drifts of the individual components that are used are taken into account.

 In the DPSSL, the performance curve of the laser is measured, on the one hand, during changes in the angle of rotation δ of the etalon 5; 14 with a constant length of the cavity and, on the other hand, during changes in the length of the cavity and constant angle of rotation δ , that is, when the etalon 5; 14 is stationary. In the
25 latter case, the frequency changes continuously and, after reaching a power minimum, jumps back by a frequency step range (FSB) of the cavity. The angle of rotation δ should be less than 10° .

 The respective power maximum is approximately in the middle of a frequency step and the transmission maxima of the utilized frequency-selective
30 component are located exactly one above the other. By generating and storing a fit

curve, as it is called, conclusions can be drawn about the exact frequency response of a component, including all characteristics of the control components. In this way, by means of an inverse function of these performance curves and a suitable control, preferably a microcomputer or PC, it is possible to adjust all frequency-selective elements in an exactly synchronized manner and accordingly to traverse the maximum possible tuning range in a continuous manner. The fit curve can be generated again automatically at any time; accordingly, the computer "learns" the characteristics of the elements.

It has also proved to be possible to use the efficiency as a criterion rather than the power. With the DPSSL, this is the ratio of the radiated pump output, which increases approximately proportional to the current of the pump diode 2, to the output power of the DPSSL. By means of a regulator, the output power is held to a constant value and the current of the pump diode 2 has a minimum in the center of a frequency step and a maximum at the locations of the frequency jumps. Suitable fit curves are generated in this way.

With a plurality of frequency-selective elements in the cavity, the total transmission of all of these elements is given in a known manner by the product of all transmission functions of all elements. In addition to the adjustable elements such as cavity length and etalon, this also includes the nonadjustable frequency-selective things such as non-ideal coating of the crystals, parasitic etalons, transmission characteristics of the utilized crystals and local influencing of the elements and components by thermal effects. For continuous tuning, it is required that the selectivity of the adjustable elements in the cavity surpasses that of the rest of the elements, wherein it is then possible that the optimal working point is next to a local power minimum.

With reference to the diagrams shown in Figs. 6 and 7, a small jump resulting from an unfavorable superposition of other frequency-selective elements is detected, for example, when tuning the cavity with the piezo-actuator 20. In this case, an optimal working point for the adjustable elements of the laser can also be found by a microcomputer by means of a learning curve.

As is well-known, longitudinal side modes can come about in a standing wave cavity in single-frequency operation when the frequency-selective elements are not optimally adjusted to one another and the principal mode accordingly suffers losses, so that there remains sufficient residual amplification for a side mode and the latter can start oscillation. The elements are adjusted by the computer in such a way that side modes are suppressed effectively and to a maximum degree. In this connection, every element is located in the middle between two mode jumps.

According to an arrangement of the method, it is also possible to replace the learning characteristic in that the cavity length determining the frequency, as "finest" frequency-selective element of the laser, is tuned gradually first at small amplitudes and then with larger amplitudes. Mode jumps then take place at the edge of the tuning range which are detected and/or recorded by a suitable measurement instrument or via the output of the laser. A suitable measurement instrument of this kind can be, e.g., a Fabry-Perot stabilized on the laser. The movement of the next coarsest frequency-selective element, e.g., of the etalon, is then changed or adapted at the edge of a tuning range until there is no longer a frequency jump in the characteristic line. The entire position (movement) of the coarser frequency-selective element is then stored.

The DPSSL is advantageously a laser whose cavity is in the order of magnitude of about several millimeters or less. In order to tune the laser, the piezo-actuator is provided with a fixed etalon, wherein the selected frequency step range FSB of the etalon is greater than the amplification bandwidth of the laser crystal and the fineness is selected in such a way that a more secure single-frequency operation is ensured with the maximum tuning range.

The etalon can also move in order to achieve a larger tuning range.

The subject matter of the application is not limited only to diode pumped solid state lasers with frequency doubling, but can also be extended to solid state lasers emitting radiation with a multiplication of (n-times) the fundamental frequency, where n is greater than 2. Accordingly, for example, a multiplication of

state lasers emitting radiation with a multiplication of (n-times) the fundamental frequency, where n is greater than 2. Accordingly, for example, a multiplication of frequency in which a plurality of suitable, nonlinear crystals are arranged subsequent to the laser crystal can be achieved by an arrangement.

- 5 While the foregoing description and drawings represent the present invention, it will be obvious to those skilled in the art that various changes may be made therein without departing from the true spirit and scope of the present.

11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
1025
1026
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062
1063
1064
1065
1066
1067
1068
1069
1070
1071
1072
1073
1074
1075
1076
1077
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090
1091
1092
1093
1094
1095
1096
1097
1098
1099
1100
1101
1102
1103
1104
1105
1106
1107
1108
1109
1110
1111
1112
1113
1114
1115
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
1150
1151
1152
1153
1154
1155
1156
1157
1158
1159
1160
1161
1162
1163
1164
1165
1166
1167
1168
1169
1170
1171
1172
1173
1174
1175
1176
1177
1178
1179
1180
1181
1182
1183
1184
1185
1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199
1200
1201
1202
1203
1204
1205
1206
1207
1208
1209
1210
1211
1212
1213
1214
1215
1216
1217
1218
1219
1220
1221
1222
1223
1224
1225
1226
1227
1228
1229
1230
1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
1244
1245
1246
1247
1248
1249
1250
1251
1252
1253
1254
1255
1256
1257
1258
1259
1260
1261
1262
1263
1264
1265
1266
1267
1268
1269
1270
1271
1272
1273
1274
1275
1276
1277
1278
1279
1280
1281
1282
1283
1284
1285
1286
1287
1288
1289
1290
1291
1292
1293
1294
1295
1296
1297
1298
1299
1300
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312
1313
1314
1315
1316
1317
1318
1319
1320
1321
1322
1323
1324
1325
1326
1327
1328
1329
1330
1331
1332
1333
1334
1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368
1369
1370
1371
1372
1373
1374
1375
1376
1377
1378
1379
1380
1381
1382
1383
1384
1385
1386
1387
1388
1389
1390
1391
1392
1393
1394
1395
1396
1397
1398
1399
1400
1401
1402
1403
1404
1405
1406
1407
1408
1409
1410
1411
1412
1413
1414
1415
1416
1417
1418
1419
1420
1421
1422
1423
1424
1425
1426
1427
1428
1429
1430
1431
1432
1433
1434
1435
1436
1437
1438
1439
1440
1441
1442
1443
1444
1445
1446
1447
1448
1449
1450
1451
1452
1453
1454
1455
1456
1457
1458
1459
1460
1461
1462
1463
1464
1465
1466
1467
1468
1469
1470
1471
1472
1473
1474
1475
1476
1477
1478
1479
1480
1481
1482
1483
1484
1485
1486
1487
1488
1489
1490
1491
1492
1493
1494
1495
1496
1497
1498
1499
1500
1501
1502
1503
1504
1505
1506
1507
1508
1509
1510
1511
1512
1513
1514
1515
1516
1517
1518
1519
1520
1521
1522
1523
1524
1525
1526
1527
1528
1529
1530
1531
1532
1533
1534
1535
1536
1537
1538
1539
1540
1541
1542
1543
1544
1545
1546
1547
1548
1549
1550
1551
1552
1553
1554
1555
1556
1557
1558
1559
1560
1561
1562
1563
1564
1565
1566
1567
1568
1569
1570
1571
1572
1573
1574
1575
1576
1577
1578
1579
1580
1581
1582
1583
1584
1585
1586
1587
1588
1589
1590
1591
1592
1593
1594
1595
1596
1597
1598
1599
1600
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
1617
1618
1619
1620
1621
1622
1623
1624
1625
1626
1627
1628
1629
1630
1631
1632
1633
1634
1635
1636
1637
1638
1639
1640
1641
1642
1643
1644
1645
1646
1647
1648
1649
1650
1651
1652
1653
1654
1655
1656
1657
1658
1659
1660
1661
1662
1663
1664
1665
1666
1667
1668
1669
1670
1671
1672
1673
1674
1675
1676
1677
1678
1679
1680
1681
1682
1683
1684
1685
1686
1687
1688
1689
1690
1691
1692
1693
1694
1695
1696
1697
1698
1699
1700
1701
1702
1703
1704
1705
1706
1707
1708
1709
1710
1711
1712
1713
1714
1715
1716
1717
1718
1719
1720
1721
1722
1723
1724
1725
1726
1727
1728
1729
1730
1731
1732
1733
1734
1735
1736
1737
1738
1739
1740
1741
1742
1743
1744
1745
1746
1747
1748
1749
1750
1751
1752
1753
1754
1755
1756
1757
1758
1759
1760
1761
1762
1763
1764
1765
1766
1767
1768
1769
1770
1771
1772
1773
1774
1775
1776
1777
1778
1779
1780
1781
1782
1783
1784
1785
1786
1787
1788
1789
1790
1791
1792
1793
1794
1795
1796
1797
1798
1799
1800
1801
1802
1803
1804
1805
1806
1807
1808
1809
1810
1811
1812
1813
1814
1815
1816
1817
1818
1819
1820
1821
1822
1823
1824
1825
1826
1827
1828
1829
1830
1831
1832
1833
1834
1835
1836
1837
1838
1839
1840
1841
1842
1843
1844
1845
1846
1847
1848
1849
1850
1851
1852
1853
1854
1855
1856
1857
1858
1859
1860
1861
1862
1863
1864
1865
1866
1867
1868
1869
1870
1871
1872
1873
1874
1875
1876
1877
1878
1879
1880
1881
1882
1883
1884
1885
1886
1887
1888
1889
1890
1891
1892
1893
1894
1895
1896
1897
1898
1899
1900
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
2064
2065
2066
2067
2068
2069
2070
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
2084
2085
2086
2087
2088
2089
2090
2091
2092
2093
2094
2095
2096
2097
2098
2099
2100
2101
2102
2103
2104
2105
2106
2107
2108
2109
2110
2111
2112
2113
2114
2115
2116
2117
2118
2119
2120
2121
2122
2123
2124
2125
2126
2127
2128
2129
2130
2131
2132
2133
2134
2135
2136
2137
2138
2139
2140
2141
2142
2143
2144
2145
2146
2147
2148
2149
2150
2151
2152
2153
2154
2155
2156
2157
2158
2159
2160
2161
2162
2163
2164
2165
2166
2167
2168
2169
2170
2171
2172
2173
2174
2175
2176
2177
2178
2179
2180
2181
2182
2183
2184
2185
2186
2187
2188
2189
2190
2191
2192
2193
2194
2195
2196
2197
2198
2199
2200
2201
2202
2203
2204
2205
2206
2207
2208
2209
2210
2211
2212
2213
2214
2215